Environmental Management (2011) 48:1107–1121
DOI 10.1007/s00267-011-9697-1

Forest Insect Pest Management and Forest Management in China: An Overview

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Received: 15 May 2010 / Accepted: 14 May 2011 / Published online: 12 June 2011

Abstract According to the Seventh National Forest Inventory (2004–2008), China's forests cover an area of 195.45 million ha, or 20.36% of the total land area. China has the most rapidly increasing forest resources in the world. However, China is also a country with serious forest pest problems. There are more than 8,000 species of potential forest pests in China, including insects, plant diseases, rodents and lagomorphs, and hazardous plants. Among them, 300 species are considered as economically or ecologically important, and half of these are serious pests, including 86 species of insects. Forest management and utilization have a considerable influence on the stability and sustainability of forest ecosystems. At the national level, forestry policies always play a major role in forest resource management and forest health protection. In this paper, we present a comprehensive overview of both achievements and challenges in forest management and insect pest control in China. First, we summarize the current status of forest resources and their pests in China. Second, we address the theories, policies, practices and major national actions on forestry and forest insect pest management, including the Engineering Pest Management of China, the National Key Forestry Programs, the Classified Forest Management system, and the Collective Forest Tenure Reform. We analyze and discuss three representative plantations—*Eucalyptus*, poplar and Masson pine plantations—with respect to their insect diversity, pest problems and pest management measures.

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Keywords Forest management · Classified forest management · Plantation · Ecological pest management · Pest control

Introduction

China's forest cover was merely 8.6% in 1949 (State Forestry Administration 2005). However, according to the Seventh National Forest Inventory (2004–2008) (State Forestry Administration 2010a), China's forests cover an area of 195.45 million ha, or 20.36% of the total land area, an increase of 20.54 million ha (2.15%) from the previous inventory (1999–2003). In 2008, the total volume of standing timber and growing stock volume was estimated to be 14.913 and 13.721 billion m^3, respectively. Annual increase in timber volume was 572 million m^3 while annual average harvest volume was 379 million m^3. China has become the nation with the fastest-growing forest resources in the world (State Forestry Administration 2008).

However, there are still many problems that cause serious concerns. The main challenges of China's forests are as follows (State Forestry Administration 2010a): (1) Forest resources on a per capita basis are very low. China's forest coverage rate is only about 2/3 of the world average and ranks 139th in the world. Forest area and forest reserve on a per capita basis are 0.145 ha and 10.151 m^3, about 1/4 and 1/7 of the world average, respectively. (2) Forest stock volume per hectare is only 85.88 m^3, about 78% of the world average. (3) The task of protection and development of forest resources is very arduous. Illegal logging activities still exist; the overall ecological function of forest ecosystems is very fragile; and various types of forest pests (diseases, insects, rodents and lagomorphs, and hazardous

plants), are distributed in a wide range of areas, cause very serious losses. In 2010, about 11.52 million ha of forests were infested by various kinds of forest pests, including 8.73 million ha by insect pests, 1.37 million ha by plant diseases and 1.43 million ha by rats and hares. Among these, 87,300 ha were considered to be serious outbreak areas (State Forestry Administration 2011b).

In facing these challenges, forest managers, stakeholders and researchers must pay more attention to forest health, the mechanisms of ecosystem stability, and the approaches to achieve forest sustainability. In this paper, we discuss the current status of forest resources and their pests, and the theories, policies and practices in forest insect pest management as well as forest management in China. We present a comprehensive overview on both achievements and challenges of forest management and insect pest control in China.

Status of Forest Insect Pests in China

There are more than 8,000 species of potential forest pests in China, including over 5,000 species of forest insect pests, nearly 3,000 species of pathogens, 160 species of rodents and lagomorphs, and 150 species of hazardous plants. Among them, 300 species are considered to be economically or ecologically important, and half of these are serious pests, including 86 species of insects (see Appendix for details). During the tenth Five Year Plan (2001–2005), the annual total area infested by forest pests was almost 10 million ha in China. The total area infested by forest pests increased from 7 million ha in 1996 to 12 million ha in 2007, causing direct economic losses of RMB 7.2 billion in 1996 and RMB 23.6 billion in 2007. Unless otherwise noted, all data in this section are from the General Station of Forest Pest Management (2009), a subordinate department of the State Forestry Administration (SFA), and also the highest body of forest pest management in the Chinese government.

Indigenous Species of Forest Insect Pests

The pine caterpillars are a group of Lepidopteran species in the genus *Dendrolimus* that feed on conifers, and have been considered the worst forest pest in Chinese history. In recent years, the area annually infested by the pine caterpillar has been estimated to be greater than 1.4 million ha. In many places, particularly in southern China, there are still frequent outbreaks.

The Asian longhorned beetle, *Anoplophora glabripennis* (Motschulsky) and other xylophagous beetles are major pests of broadleaf plantations (*Populus* spp., *Salix* spp., *Ulmus* spp., *Robinia* spp., *Betula* spp., *Acer* spp., etc.) in northern China. Significant losses attributed to the Asian longhorned beetle were not recorded until the 1980s, when vast tracks of poplars were grown as shelterbelt trees (FAO 2007). In the 1990s, there were serious outbreaks of xylophagous beetles including *A. glabripennis* (Coleoptera: Cerambycidae) and *Apriona germari* (Hope) (Coleoptera: Cerambycidae) in some western provinces (or autonomous regions), which caused disastrous damage to the Three-North Shelterbelt Program. Despite large-scale control efforts that were undertaken in these regions, the infestations and related economic and ecological losses have not been significantly reduced. Statistics for 2005–2007 show the overall infestation areas of poplar wood borers in China to be 0.71, 0.84, and 0.89 million ha, respectively.

In recent years, poplar defoliators, e.g. *Apocheima cinerarius* Erschoff (Lepidoptera: Geometridae) and *Clostera anachoreta* (Fabricius) (Lepidoptera: Notodontidae), have become common disruptive insect pests. Between 2005 and 2007, areas infested with poplar defoliators in China have been 0.88, 1.14, and 1.42 million ha, respectively.

In addition, *Massicus raddei* Blessig (Coleoptera: Cerambycidae), *Tomicus piniperda* (Linnaeus) (Coleoptera: Scolytidae) and some other species that have rarely caused any significant damage in the past have occurred at outbreak levels in recent years.

Exotic Forest Insect Pests

As of 2008, 34 invasive alien forest pest species that seriously threaten the forests in China have been recorded. Among the forest pest outbreaks in China, about 20% of the total infestation area has been caused by invasive alien pests, with losses incurred by them reaching as high as 60%. According to incomplete statistics, invasive forest pests damage an area of about 1.3 million ha annually, resulting in estimated ecological and economic losses of RMB 73.5 billion (State Forestry Administration 2010b). In short, the problem of invasive species has become a serious threat to China's ecosystems. The most destructive of such insect species are listed in Appendix. Examples include *Hyphantria cunea* (Drury) (Lepidoptera: Arctiidae) on various broadleaf trees in northern China; *Dendroctonus valens* Leconte (Coleoptera: Scolytidae) on pine trees in Shanxi, Shaanxi, Henan and Hebei provinces; *Heterobostrychus aequalis* (Waterhouse) (Coleoptera: Bostrychidae) in some southern provinces; *Brontispa longissima* (Gestro) (Coleoptera: Hispidae) on palm trees in Hainan, Guangxi and Guangdong provinces; and more recently, *Leptocybe invasa* Fisher & LaSalle (Hymenoptera: Eulophidae) on *Eucalyptus* spp. trees in Guangxi, Guangdong and Hainan provinces.

Insect Pest Occurrence in Three Typical Plantations

Due to historical over-exploitation, large areas of the country's natural forest resources have been transformed into secondary forests and shrubs. Thus since the 1960s, China has invested heavily in forest plantations to meet the demands for forest goods and services (Deng and Li 2009). Currently the area of natural forests is 119.69 million ha. There are 61.69 million ha of plantations, which comprise more than 30% of the country's total forest area, the highest of any country in the world (State Forestry Administration 2010a). However, young- and middle-aged plantations account for 68% of the total plantation area, and the problems associated with young, single-species plantations are fairly conspicuous. Chinese fir (*Cunninghamia lanceolata*), Masson pine (*Pinus massoniana*) and poplar (*Populus* spp.) account for 59.41% of the total plantation area in the country. Over 60% of the plantations in Qinghai, Xinjiang, Inner Mongolia, Jiangsu provinces (or autonomous regions) are poplar stands; over 60% of the plantations in Guangxi, Anhui, Guangdong, Chongqing, Hubei provinces (or autonomous regions, municipalities) are Chinese fir and Masson pine stands; more than 50% of the plantations in Hunan, Zhejiang, Guizhou, Jiangxi and Fujian provinces consist of Chinese fir stands; over 50% of the plantations in Heilongjiang and Jilin provinces are larch forests; and finally, more than 50% of the plantation areas in Hainan province are comprised of *Eucalyptus* spp. (General Station of Forest Pest Management 2009). With such large-scale plantation development, a number of problems related to even-aged pure stands have become more and more prominent. In the following sections, we outline the insect diversity and pest-related problems in three typical plantations in China.

Eucalyptus Plantations

Eucalyptus is a diverse genus in the myrtle family (Myrtaceae). Worldwide *Eucalyptus* cultivation areas (mainly in the tropics and subtropics) encompass 19.61 million ha. China accounts for about 13% of the world's total, or some 2.61 million ha, third only to India and Brazil (GIT Forestry Consulting 2009). *Eucalyptus* were first planted in China more than 100 years ago, and now has been introduced in 16 provinces of southern China as an important fast-growing tree species for industrial raw materials (Zhao and others 2007; Wang and others 2008). However, it is generally believed that *Eucalyptus* plantations, especially as monocultures, may frequently lead to a variety of ecological problems, such as land degradation, biodiversity loss and groundwater decline (Zhao and others 2007; Ma and others 2006; Li and others 2006a). Thus in China *Eucalyptus* spp. are also among the most controversial non-native tree species (Wang and others 2008).

Compared to other species in pure or mixed plantations and to natural forests, pure *Eucalyptus* plantations are more prone to contribute to the decline of insect diversity (Wang and others 2008; Luo and others 2007) while favoring greater incidence of insect pests (Bragança and others 1998; Chen and Gu 2000; Gu and Hong 2006; Lin and others 2006). Chen and Gu (2000) reported that at least 207 species of insects have been found feeding on *Eucalyptus* in China, belonging to 10 orders and 50 genera. Of these, 149 species are distributed in the Oriental Region. No species of *Eucalyptus* pests that are endemic to Australia have been found in China (Chen and Gu 2000). All these pests are native species including over twenty that cause severe damage. Recently, however, *L. invasa* Fisher & LaSalle (Hymenoptera: Eulophidae), a newly-described invasive gall-making wasp species that is likely from Australia, was detected on of *Eucalyptus* spp. in Guangxi, Guangdong and Hainan provinces. The *L. invasa* infestation rate in the *Eucalyptus* stands recently approached 100% and severely weakened and eventually stunted the growth of trees (Wu and others 2009).

Serious pest problems and low insect diversity in *Eucalyptus* plantations are frequently attributed to the low diversity of plant communities and the simple structure of insect communities (Gu and Hong 2006; Lin and others 2006). However, the problem is not unique to *Eucalyptus* plantations; rather, it is a common drawback of many plantations, such as poplar, rubber, and Chinese fir among others.

Poplar Plantations and Poplar Longhorned Beetles

Poplar plantations and poplar longhorned beetles in the Three North Region of China is another example of serious pest attacks being inspired by pure stands. Cerambycid species that feed on *Populus* trees are collectively referred to as poplar longhorned beetles. There are more than 100 species of poplar longhorned beetles in China, but only a few species are seriously destructive, including *Anoplophora glabripennis* (Motschulsky), *Apriona germari* Hope and *Batocera horsfieldi* (Hope) (Coleoptera: Cerambycidae). Among these, the Asian longhorned beetle *A. glabripennis* is the most destructive and widespread (Pan 2005). Poplar longhorned beetles have caused widespread mortality of poplar, willow and elm throughout vast areas of China, leading to great economic losses, especially in Northern China. Because of the outbreak of poplar longhorned beetles, the plantations established during the first phase of the Three-North Shelterbelt Program were nearly destroyed, and more than 80% of poplar stands planted during the second phase were damaged (Ye 2000; Wang and others 2000; Luo and others 2000). The life span of

infected poplar was shortened to about 10 years in areas infested by longhorned beetles (Ye 2000; Luo and others 2000). In 2002, the infested area of poplar longhorned beetles was about 0.6 million ha (Pan and others 2005).

Recently a growing number of ecologists and plant protection scientists have recognized that the pest problem of poplar plantations in northern China is fundamentally an ecological problem (Luo and others 2000; Zhang and others 2002; Pan and Wu 2001; Hao and others 2004). First, the fragile ecological environment in these regions, which are characterized by an arid climate, strong winds, low rainfall, sparse vegetation, frequent anthropogenic disturbance, low species richness and abundance of natural enemies, provided favorable conditions for poplar disease and insect pests (Zhang and others 2002). Second, the areas of pure poplar stands are extremely large, and the selection of tree species was based mainly on growth characteristics without consideration of pest resistance (Zhang and others 2002). Third, in the early days the operational focus was primarily on chemical control with highly toxic and broad-spectrum insecticides, which not only eliminated the pests but also killed their natural enemies as well as other organisms in the ecosystem (Zhang and others 2002; Pan 2005). Fourth, little attention was paid to pest quarantine and monitoring. There were poor communications among the forest sectors involved in forest pest control, quarantine and monitoring. At the same time, infested trees could not be detected and treated in time before the expansion of infestations (Pan 2005). In short, the initial plantation design for pure poplar stands, a fragile ecological environment, and poor management are no doubt the main reasons for pest outbreaks in the Three-North Region of China.

Several measures have been used for the control of longhorned beetles in the Three-North Region, as detailed in a number of research reviews over the past ten years (see Luo and others 2000; Wang and others 2000; Pan and others 2005). Physical and chemical control measures for individual beetles and infested trees include removing eggs and killing larvae and adults by hand, trunk injections with pesticides, blocking the larvae (frass) holes with insecticide impregnated mud, spraying pesticides directly on adults, cutting damaged branches, sanitation felling to prevent the spread of the beetles, and grafting Chinese white poplar or other resistant trees onto original poplar stumps (Pan 2005). Silvicultural management measures include selecting and introducing insect-resistant clones, varieties and trees species; planting trap trees (these are planted to lure adult beetles to lay eggs, which are then removed and destroyed); irrigation; fertilization; timely thinning and pruning; and designing mixed stands with different tree species (non-host, pest-resistant tree and trap tree) to regulate the structure of the forest (Wang and others 2000; Pan 2005). Biological control agents include woodpeckers, fungal entomopathogenic and entomophilic nematodes, the parasitic wasp *Scleroderma guani*, and the insect predator *Dastarcus helophoroides* (Wang and others 2000; Pan 2005).

The overall recommendations for longhorned beetle management include implementing the strategy of "Integrated Pest Management with Emphasis on Prevention"; strengthening quarantine and inspection; matching tree species to site conditions; establishing mixed plantations; using trap trees and new biological control technologies; developing and applying pheromone traps; and training local residents to improve their knowledge of forest management and pest control (Luo and others 2000; Pan 2005). In some pilot areas, the damage/infestation of poplar longhorned beetles has been efficiently controlled as a result of the aforementioned integrated measures (see Luo and Li 1999; Yan and Yan 1999; Pan 2005). But there is a dilemma in a large-scale application of the suggested control measures. On the one hand, despite recommendations for mixed planting of resistant tree species, many farmers still chose to plant susceptible trees because of the shortage and high costs of the resistant species (Pan 2005). As another example, the recommended ratio of resistant trees, non-host trees and trap trees was 45–50:45–50:5–10% (Luo and Li 1999). In a pilot study, up to 20 tree species were selected for establishing mixed stands (Luo and Li 1999). In reality, few afforestation programs or stand improvement efforts can achieve such high standards and complexity.

When either technical or economic feasibility is lacking the success of a forest pest management program cannot be guaranteed, since in essence they are the two sides of the same coin. That may be why outbreaks of longhorned beetles in the Three-North Region still occur from time to time, although many national projects have been implemented to combat this destructive insect pest in that region since the 1980s. In addition, as discussed in the previous section, the fragile ecological environment in the Three-North Region is not conducive to the long-term stability of large-scale plantation ecosystems, which is probably the fundamental cause of the insect pest problems in this region. In arid and semi-arid areas (like most parts of the Three-North Region), grasslands dominated by xerophytic herbs, semi-shrubs or shrubs as the main form of natural vegetation cannot and should not be replaced by forestlands. Protection and restoration of natural vegetation in the Three-North Region is the recommendation of many ecologists.

Masson Pine Plantations and Pine Caterpillar

Masson pine (*Pinus massoniana*) is native to a wide area in central and southern China, and it is the most widely

distributed pine species and most important timber species in southern China. The entire tree can be used for different economic purposes. It is often planted as a pioneer species in the restoration and reconstruction of subtropical mountain forest ecosystems (Gu 1995). However, due to overemphasis on rapid afforestation, a large proportion of Masson pine plantations in southern China are pure stands (Fan 2007; Deng and Li 2009). The productivity and ecological problems of Chinese Masson pine plantations have been reviewed by Deng and Li (2009).

The Masson pine caterpillar, *Dendrolimus punctatus* (Walker) (Lepidoptera: Lasiocampidae) is a major forest pest in China, and both its wide distribution and damage rank as first in the country. The outbreak mechanism of this species has been intensively studied. The biological and genetic characteristics of the Masson pine caterpillar and the existence of large-scale pure pine forest stands are considered to be the two critical contributing factors (Zhang and Li 2008).

Causes of Insect Pest Outbreaks in Forest Plantations

Plantation forests, especially pure stands, have been criticized for leading to frequent pest outbreaks, although the subject remains controversial (see Gadgil and Bain 1999; Carnus and others 2003; Jactel and Brockerhoff 2007; Vehviläinen and others 2007). The following are considered to be the main causes for serious pest problems in monoculture forest plantations: (1) lack of natural enemies, high concentration of host plants, absence of alternative hosts, and more opportunities for development of closer coincidence between insect and plant phenology (Larsen 1995); (2) cultural operations and extensive management in plantations causing plant injury or stress may facilitate initial establishment of some insects (Nair 2001); (3) some planting sites (drought-prone, water-logged, acidic or alkaline soil, etc) may be unsuitable for the target tree species (Nair 2001). Three frequently cited hypotheses explaining the effects of plant species diversity on herbivory are the associational resistance hypothesis (Tahvanainen and Root 1972), the enemy hypothesis (Elton 1958a) and the resource concentration hypothesis (Root 1973). More recently, a "semiochemical diversity" hypothesis was proposed by Zhang (2001) and Zhang and Schlyter (2003), which states that mixed habitats with higher diversity of plant volatiles may disturb olfactory-guided host choice and reduce the risk of outbreaks of specialist herbivores. Certain life history traits and phylogeny of insects may promote population outbreaks, including greater fecundity, poor flying ability of females, eggs laid in masses, and gregarious caterpillar behavior (Hunter 1991). In addition, the Moran effect was identified as an important mechanism for synchronized pest outbreaks over large spatial scales (Williams and Liebhold 2000; Peltonen and others 2002); however, no detailed studies on this phenomenon are available as yet in China.

While few rigorous experimental studies have examined these mechanistic hypotheses in China, several have discussed the diversity–stability relationships. For example, in Masson pine forests, it was shown that the more diverse plant communities support more insect species (Li and others 1998; Han and Zhang 2000; Liu and others 2005; Li and Zhang 2001). As an important component of biodiversity, insect diversity plays an important role in maintaining the ecological stability and productivity of ecosystems (Jiang and Pi 2004). For example, a study on Masson pine forests by Zhang and others (1998) showed that the greater the insect diversity, the stronger the stability of insect communities, which supported the diversity–stability hypothesis (MacArthur 1955; Elton 1958b). With respect to diversity–stability relations, we recognized the argument by Liu (1991), who proposed that systems can be categorized as parallel-structured or series-structured. In the latter, stability is negatively correlated with complexity; while in parallel-structured systems it is positively correlated with complexity. In this sense, neutral insects (neither strongly harmful nor beneficial to plants) might play certain roles in the diversity and stability of the overall insect community. Many earlier studies have emphasized the regulating effects of natural enemies on target pests. However, Zhang and others (1998) found that the strongest inhibitory effects on pine caterpillars were from other phytophagous insects, followed by parasitic insects and predators, which suggests that competition within the same trophic level may be very important for the stability of the insect community. On the one hand, more phytophagous insects lead to more intense competition with target pests (pine caterpillars); on the other hand, the diversity of phytophagous insects enhances the diversity of natural enemies, and then the entire insect community tends to act as a complex system with a parallel structure, which in turn increases the stability of the system (Zhang and others 1998, 2005).

Proposed explanations for the causes of serious pest outbreaks in China's plantations are not limited to the commonly recognized factors such as low biodiversity, young-aged forest stands, simple community structure, and reduced soil fertility (Hao and others 2004; Lei and Xiao 2008). Others include unfavorable site conditions for large-scale afforestation, newly established plantations that are not well protected as a forest enclosure, and not matching tree species to site conditions due to overemphasis on rapid afforestation (Qin and others 2005; Xue and others 2007). In addition, serious forest pest outbreaks in China have also been attributed to abnormal climate, an increase in invasive pests due to more frequent international trade, inadequate financial investment in pest prevention and control, and

outdated management technologies and measures in forest pest control (General Station of Forest Pest Management 2009).

Forest Insect Pest Management in China

Organizational Structure

The organizational structure for forest pest control in China consists of agencies at the national level (including the Afforestation Department, SFA and the General Station of Forest Pest Management within the SFA) and agencies at local levels (province, city and county). The major responsibilities of the national pest control agencies include: (1) formulating regulations, policies and medium- and long-term plans; (2) leading and organizing forest pest forecasting, forest plant quarantine operations and the control of major forest pest outbreaks; (3) developing and promoting pest control technologies; (4) providing consulting and training services. The forest pest control agencies at local levels are administratively supervised by the local forestry departments, are mainly in charge of forest pest forecasting, quarantine and the prevention and control of forest pest outbreaks within their areas of jurisdiction. At present, there are 3,067 forest pest control agencies throughout China, including 34 provincial agencies, 373 municipal sectors and 2,660 county-level agencies. There are no specialized pest control agencies below the county level, and pest-related matters are addressed by the township forestry stations (General Station of Forest Pest Management 2009).

Guiding Theories of Forest Pest Control

According to the General Station of Forest Pest Management (2009), the theories and practices of forest pest control have gone through three major periods in China: (1) between 1949 and 1975, chemical control was the dominant method of pest control, with the eradication of pests as the overarching goal; (2) following the landmark National Plant Protection Conference held in 1975, in which the policy of Integrated Pest Management (IPM) with Emphasis on Prevention was introduced, pest control from 1976 to 1995 was guided by IPM; (3) from 1996 to the present, Sustainable Pest Management (SPM) has become the guiding theory in forest pest control. SPM integrates the ideas of IPM and "Sustainable Forestry/Development". It aims to achieve sustainability at multiple spatial and temporal scales, focuses largely on prevention and natural control, and acts cautiously with any direct control measures that might harm the environment, even when pest populations exceed economic injury levels (Luo and Shen 1998; General Station of Forest Pest Management 2009). However, we believe that there is no distinct point in time demarcating the boundary between the second and third periods. Today in China various theories and technical systems coexist, including IPM (Liu 1989; Zhao and others 2003; Chen and Han 2005), ecological pest management (Ding 1993; Yan and Yan 1999; Guo 2003; Liang and Zhang 2004, 2005) and SPM (Zhang 1999; Pan and others 1999).

In 1997, the "Engineering Management of Forest Pests" was formally put forward by the former Ministry of Forestry (now the SFA) as part of the "Decision on Further Strengthening the Prevention and Control of Forest Plant Diseases and Insect Pests". The "Decision" pointed out that the management of any important forest pests should, under the unified leadership of the central state, formulate prevention and control programs, delimit the epidemic areas, and implement engineering pest management. Soon afterwards, three national pilot programs of engineering pest management were launched for combating the Chinese pine caterpillar outbreak in western Liaoning province, the Asian longhorned beetle outbreak in Inner Mongolia and the pinewood nematode outbreak in Guangdong province (Li and others 2007). Since 2000, the SFA further expanded the areas of engineering pest management, and launched national programs for six major forest pests—the pinewood nematode (*Bursaphelenchus xylophilus*), the red turpentine beetle (*Dendroctonus valens*), the American white moth (*Hyphantria cunea*), the poplar longhorned beetle, the pine caterpillar, and forest rats (Pan and Wu 2001; Li and others 2007). These programs cover 28 provinces and autonomous regions, including municipalities and three forest industry groups, in a total of 1,827 counties (Wei 2005). Since 1997, the term "Engineering Management of forest pests" has frequently appeared in the documents of forestry sectors. It is considered as the application of systematic engineering management to sustainable pest control, and it aims at integrating the theories of Biological Pest Management, Ecological Pest Management and SPM (Pan and others 1999). Interestingly, it has not been widely adopted as a pest management theory by plant protection scientists so far. In practice, it was often understood as a project management process, including planning, design, documentation/reporting, approval, implementation, inspection and evaluation, etc (Li 2001). In addition, although since 2000 the central government has invested more than RMB 200 million in the engineering management programs and RMB 174 million in disaster relief funds to combat the aforementioned six major forest pests (Wei 2005), the funding for pest control has still been far less than the actual demand (Guo and others 2005). Under the existing prevention and control system, the efficacy of pest control strongly depends on

adequate financial input; thus increasing national investment undoubtedly increases the chance for success.

National Policies and Regulations

The Forest Law of the People's Republic of China (Standing Committee of the National People's Congress 1998), the Regulations on the Prevention and Control of Forest Plant Diseases and Insect Pests (State Council 1989), and the Regulation on Plant Quarantine (State Council 1992) constitute the major legal basis of forest pest management in China. In recent years, a series of regulations related to pest management were issued by the Chinese government, including the Regulation on the Implementation of the Forestry Law (State Council 2000), Management Measures for the Production of Pesticides (State Development and Reform Commission 2004), Measures for the Treatment of Unexpected Harmful Forest Biological Events (State Forestry Administration 2005), and the Decision on Amending the Measures for Implementing the Regulation on Pesticide (Ministry of Agriculture 2007). Since these measures were adopted, knowledge continues to evolve and some previously accepted ideas and terms have not proven adequate for new situations in forestry and social development (Guo and others 2005; Song 2010). In order to adapt to and complement recent reforms related to forest ownership, some Chinese scholars (e.g., Song 2010) have suggested a number of potential actions to improve forest pest management in China, including refinement of laws, regulations and relevant policies, transforming functions of forestry stations at the township level, establishing and improving the social service system, and devising innovative investment mechanisms for forest pest control.

Strategies and Measures of Insect Pest Management in Plantations

Plantations are not necessarily unhealthy forests. For example, a study by Gadgil and Bain (1999) found that the reduced growth or mortality caused by pests and abiotic disturbances were generally less in intensively managed, planted forests than in natural forests. Many strategies and measures have been proposed and applied for pest management in plantation forests in China. For example, beginning in the early 1980s, IPM of pine caterpillars and poplar longhorned beetles was implemented in some pilot areas, such as counties in Zhejiang, Anhui, Liaoning, Shanxi, and Shandong Provinces (Liu 1989). Currently, the most accepted strategy or theory is Ecological Pest Management (Gao 1999; Hao and others 2004), which was first proposed by Tshernyshev (1995). Traditional forest pest management approaches, such as chemical control and IPM, usually focus on the health of trees and often adopt direct methods to deal with target insect pests and disease. However, Ecological Pest Management focuses upon the integrity, stability and health of the forest ecosystem. Methods used in Ecological Pest Management usually include: (1) silvicultural measures, e.g., the regulation of site conditions and stand improvement; (2) application and development of host resistance; (3) biological control methods, e.g., biopesticides and natural enemies including pathogenic microorganisms and beneficial insects; (4) pheromone control; and (5) use of environmentally friendly pesticides and chemical pesticides as emergency control measures (Liang and Zhang 2004). Many forest scientists and ecologists stress that silvicultural measures which are based on ecological theories are an important aspect of modern forest pest management (Gao and others 1992; Kaufmann and Regan 1995; Larsen 1995). A major principle in silviculture is that the tree species used for afforestation should be adapted to the site conditions (climate, soil, etc). Conversion of pure stands to mixed-species stands is the most important silvicultural measure for pest control. For example, a suggestion for controlling the insect pests in *Eucalyptus* plantations is to alter tree species composition and increase herbaceous cover, which will be beneficial to the diversity and stability of insect communities (Yao 2009). Similarly, converting monocultures to mixed forests is a critical approach to control insect pest outbreaks in pure stands of Masson pine (Fan 2007; Xue and others 2007).

Stand improvement can be considered as a form of ecological engineering. The overall purpose of stand improvement is to improve the economic or ecological value of forest stands by adjusting the composition and structure of plant communities (Chen 2008). For instance, currently Guangdong province is making great efforts to promote forest stand improvement (Xue and others 2007). To ensure the progress of such projects, the State Forestry Administration (2007) promulgated the Technical Regulations on Reconstruction of Low-function Forest. According to the Seventh National Forest Resources Inventory (2004–2008) a positive trend is reflected in the increased proportion of mixed stands, up by 9.17 percent compared with that from the previous inventory (1999–2003) (State Forestry Administration 2010a). Many forest stand improvement projects have already achieved positive results with respect to stand quality and pest control. For example, a simple-structured landscape forest which was seriously infested by the pinewood nematode in Nanjing was converted to an uneven-aged and multi-layered mixed forest, resulting in a significant decline of insect pests and diseases and an improvement in the aesthetic character of the landscape (Li and others 2006b). In addition, many

investigations have shown that insect diversity increased in the process of vegetative restoration activities such as forest enclosure (Gao and others 1992) and the conversion of pure stands to mixed stands (Ma and Liu 2007; Zhang and You 2007). However, due to technical and economic constraints, it is unlikely that all single-species stands will be converted into mixed-species stands simply for the purpose of reducing pest damage. Alternative options for preventing the development of insect pest outbreaks might include increasing understory plant diversity in plantations and/or enhancing habitat diversity at the landscape level (Carnus and others 2003).

Integrating Pest Management within a New Era of China Forestry

Forest management and utilization have a considerable influence on the stability and sustainability of forest ecosystems (Larsen 1995). At the national level, forestry policies play a decisive role in forest resource management and forest health protection, particularly in China where forestry reform is underway. A new era of China's forestry began with the implementation of the Six National Forestry Programs (Zhang and others 2004).

National Key Forestry Programs

In 2001, the China State Council approved the Six Key Forestry Programs (SKFPs) proposed by the State Forestry Administration of China (SFAC). These six programs are: (1) the Natural Forest Protection Program, aimed at implementing a logging ban along the upper reaches of the Yangtze and Yellow river; greatly reducing timber output in key state-owned forests in the northeastern region and Inner Mongolia and protecting natural forests in other areas; accelerating tree and grass-planting activities; and enforcing forest protection; (2) the Three-North Shelterbelt Development Program and the Shelterbelt Development Program along the Yangtze River Basin; (3) the Conversion of Cropland to Forest Program (the Grain for Green Program), which is to transfer cultivated slope lands into forests in areas with severe soil erosion, sandification and salt-alkalization by means of forest rehabilitation; (4) the Desertification Control Program in the vicinity of Beijing and Tianjin; (5) the Wildlife Conservation and Nature Reserve Development Program; and (6) the program on Development of Fast-growing and High-yield Timber Plantation Bases, aimed at relieving domestic timber-demand pressure and better protecting natural forests. To date the Six Key Forestry Programs (SKFPs) have achieved tangible results (see Wang and others 2007).

The "Five Changes" in Forestry Development

The "Five Changes" were proposed by the SFAC in 2002, and refer to the major tasks of forestry development in China. These are: (1) shifting from timber production to ecological construction; (2) shifting from logging of natural forests to harvesting plantation forests; (3) shifting from deforestation for farmland to reforestation; (4) shifting from completely free use of forest ecological benefits to paid use of the benefits; and (5) shifting from government forest management to social forestry management. In 2003, the State Council promulgated the Decision on Accelerating the Development of Forestry, which further defined national guidelines for the development of forests in a new era, namely, sustainable development with a focus on ecological construction.

Classified Forest Management

The major challenge of forest management is to find ways to meet commodity needs while conserving ecosystem functions and long-term sustainability (Kaufmann and Regan 1995). In order to strengthen forest resource management in a market economy, as well as to relieve conflicts between wood demands and the diversified needs for forest services (Dai and others 2009), in 1996 China began pilot implementation of the Classified Forest Management System (Zhou and Song 2002). In 2000, the central government accelerated the reform of forest classification management and completed the final version of the Classified Forest Management System in 2003 (Dai and others 2009). According to the Forest Law of China (Forest Law of The People's Republic of China 1998), the forest had been classified into shelterbelt forest, timber forest, economic forest, fuel forest and special-use forest. In the Classified Forest Management System, the five forest types are reclassified into two classes based on their main functions. Shelterbelt and special-use forests are now classified as ecological forests (literally translated as ecological welfare forests), and timber forests, economic forests and fuel forests are combined into one class as commercial forests. Under this new classification system, it is convenient to implement different but more appropriate management measures for different stands. For example, in commercial forest stands, genetic improvement and stand improvement should be conducted based on specific economic goals, while in ecological forest stands sustainable forest management and "close-to-nature forestry" theories should be encouraged.

Collective Forest Tenure Reform

The implementation of Classified Forest Management has also been the basis for the acceleration of reforms in the

forestland tenure system (Dai and others 2009). According to the current Forest Law (1998), China's forest resources are divided into state-owned forests and collective-owned forests. The area of collective forests accounts for 58.1% of the country's total forest area, mainly in mountainous regions (Song 2010). In some respects, old laws and practices present a major barrier to the further development of China's forestry (Song 2010). In recent years, however, the ongoing forestry reforms in China have opened the forest sector to much greater individual and corporate participation, and forest management policy has shifted direction to encourage sustainability while balancing land-use, economic growth and demand for forest products (Wang and others 2007). Collective forest tenure reform started Fujian province in 2003. Now the collective forest tenure reform has been carried out across the country in 30 provinces (or cities/prefectures). The reform encouraged collectives to allocate use rights of forest land to farmer households. By the end of 2009, the area of forest land with clearly defined forest tenure had reached 146 million ha—81.69% of the total area of collective forest land, and more than 63 million certificates had been issued to farmer households (State Forestry Administration 2011a). The reform mobilized farmers' enthusiasm for forest protection and afforestation and has shown promise for increasing forest cover and farmer incomes.

Results and Effects of Forestry Reforms

Through the implementation of these forestry policies and programs, some positive results have already been obtained. Compared to the Sixth National Forest Inventory (1999–2003), the most recent inventory (the Seventh, 2004–2008) reveals six important changes: (1) forest area and standing volume continued to increase; (2) natural forest area and stocking volume increased significantly; (3) the growth of plantation resources was rapid; (4) forest harvesting is shifting from natural to plantation forests; (5) forest quality and ecological function improved, (6) the proportion of plantations and immature forests managed by individuals increased by 11.39% to 32.08%. Thus, the collective forest tenure system reforms have achieved significant results (State Forestry Administration 2010a).

The aforementioned series of reforms and programs in forestry indicate that China is paying more attention to the increase in the total amount of forest resources while placing more and more emphasis on forest ecosystem health. Many forestry reform measures are undoubtedly beneficial to forest pest control efforts, especially classified forest management and collective forest tenure reform. As captured by two Chinese proverbs: "No one medicine can heal all illness," and "There is one key for one lock". We cannot use any single fixed model to deal with the wide variety of pest problems facing China's forests. At a minimum, pest management policies and tactics for ecological forests and commercial forests should differ (Li 2001; Liang and Zhang 2005), because the operators, beneficiaries, management goals, and even levels of financial investment are different in the two forest management systems.

Ecological forests mainly provide "public welfare services" and we believe that the management strategy for ecological forests should adopt the "Close-to-Nature Forestry" theory, and promote forest succession toward late successional stages characteristic for the region in order to enhance the stability and sustainability of forests. Therefore, pest management in ecological forests should rely mainly on the roles of natural regulation. Stand improvement in ecological forests should mainly take silvicultural measures, and establish forest enclosures. For ecologically marginal or low quality forest stands, some suitable measures might include: replanting with native broadleaved trees species, cultivating mixed forest stands, promoting forest regeneration, adjusting stand density, increasing coverage of understory vegetation, prioritizing biological control measures, and rationally and cautiously using chemical pesticides (e.g., reducing the use of broad-spectrum pesticides; using selective, low-toxicity, low-residue pesticides) (Li 2001).

Intensive pest management measures should be adopted in commercial forests in order to foster fast-growing and high-yielding timber forests, short-rotation industrial raw material forests, bamboo forests, and other forests for the production of high-value products. Most commercial forests are plantations, aimed at high-yield and high income within a scheduled time frame (Li 2001). Pest management measures in commercial forests should include silviculture, agroforestry (e.g., intercropping of trees with crops, trees with medicinal plants, and trees with shrubs), site improvement (irrigation, fertilization, etc), prioritizing biological and physical control measures, actively applying natural enemies, pheromones and biopesticides, and judicious use of chemical pesticides.

Acknowledgments We thank Dr. Liu Yan for her extensive work on searching the literature and editing of reference lists. We are indebted to several anonymous reviewers who provided very helpful comments on the manuscript. We also thank Bernard J. Lewis, formerly with the Department of Forest Resources at the University of Missouri and now Visiting Professor at Institute of Applied Ecology, Chinese Academy of Sciences, for his great help on the language editing of the paper. This research was supported by the National Natural Science Foundation of China (No. 30670306; No. 30970515) and National Special Projects for Research in Nonprofit Sectors (forestry), State Forestry Administration (200804023).

Appendix

See Table 1.

Table 1 86 species of insect pests that cause the most severe damage to forests in China (General Station of Forest Pest Management 2009)

Number	Latin name	Order	Family	Feeding guilds	Distribution in China
1	*Eotetranychus pruni*	Acarina	Tetranychidae	Sap-sucking insect	Xinjiang, Gansu
2	*Anoplophora chinensis*	Coleoptera	Cerambycidae	Woodborer	Almost nationwide
3	*Anoplophora glabripennis*		Cerambycidae	Woodborer	Almost nationwide
4	*Apriona germari*		Cerambycidae	Woodborer	Almost nationwide
5	*Batocera horsfieldi*		Cerambycidae	Woodborer	Mainly distributed in Southern China
6	*Massicus raddei*		Cerambycidae	Woodborer	Almost nationwide
7	*Monochamus alternatus*		Cerambycidae	Woodborer	Almost nationwide with the exception of Guangdong, Guangxi and Hainan
8	*Monochamus sutor*		Cerambycidae	Woodborer	Northeast China, Inner Mongolia, Shandong and Qinghai
9	*Saperda populnea*		Cerambycidae	Woodborer	Mainly distributed in Northern China
10	*Semanotus bifasciatus*		Cerambycidae	Woodborer	Mainly distributed in Northeast, North, Central, East and South China
11	*Xylotrechus rusticus*		Cerambycidae	Woodborer	Northeast China
12	*Agelastica alni orientalis*		Chrysomelidae	Defoliator	Xinjiang
13	*Diorhabda elongata deserticola*		Chrysomelidae	Defoliator	Inner Mongolia, Xinjiang, Gansu
14	*Cryptorrhynchus lapathi*		Curculionidae	Woodborer	Northeast China, Hebei, Shanxi, Shaanxi, Gansu, Xinjiang and Inner Mongolia
15	*Curculio davidi*		Curculionidae	Fruit eater	Almost in all chestnut-producing areas
16	*Cyllorhynchices cumulatus*		Curculionidae	Feed tender fruit-branch	Henan, Shandong, Hebei
17	*Cyrtotrachelus buqueti*		Curculionidae	Feed bamboo shoots	Guangdong, Guangxi, Guizhou, Sichuan
18	*Hylobitelus xiaoi*		Curculionidae	Phloem borer	Jiangxi, Hunan, Hubei, Fujian, Guangdong, Guangxi, Guizhou, Yunnan
19	*Pissodes nitidus*		Curculionidae	Boring insect	Northeast China
20	*Pissodes punctatus*		Curculionidae	Woodborer	Northwest, Southwest and North China
21	**Rhynchophorus ferrugineus*		Curculionidae	Woodborer	Fujian, Guangdong, Guangxi, Hainan, Yunnan, Hong Kong, Taiwan
22	**Brontispa longissima*		Hispidae	Feed on young leaves	Hainan, Guangdong, Guangxi, Hong Kong, Taiwan
23	*Anomala corpulenta*		Scarabaeidae	Defoliator	Almost nationwide
24	*Blastophagus* spp.		Scolytidae	Woodborer	Almost nationwide
25	*Dendroctonus armandi*		Scolytidae	Woodborer	Henan, Shaanxi, Sichuan, Hubei, Gansu
26	**Dendroctonus valens*		Scolytidae	Woodborer	Shanxi, Shaanxi, Hebei, Henan
27	*Ips subelongatus*		Scolytidae	Woodborer	Northeast China, Inner Mongolia, Hebei, Shanxi, Beijing, Xinjiang, Yunnan
28	*Tomicus piniperda*		Scolytidae	Woodborer	Jilin, Liaoning, Henan, Jiangsu, Zhejiang, Hunan, Shaanxi, Sichuan, Yunnan
29	**Heterobostrychus aequalis*		Bostrychidae	Woodborer	Guangdong, Guangxi, Hainan, Yunnan, Hong Kong, Taiwan

Table 1 continued

Number	Latin name	Order	Family	Feeding guilds	Distribution in China
30	**Carpomyia vesuviana*	Diptera	Tephritidae	Fruit eater	Xinjiang
31	*Adelges laricis*	Homoptera	Adelgidae	Gall-making insect	Northeast China, Shandong, Inner Mongolia
32	*Tettigoniella viridis*		Cicadellidae	Sap-sucking insect	Almost nationwide
33	*Eulecanium gigantea*		Coccidae	Sap-sucking insect	Hebei, Shanxi, Liaoning, Anhui, Henan, Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang
34	*Parthenolecanium corni*		Coccidae	Sap-sucking insect	Almost nationwide
35	**Hemiberlesia pitysophila*		Diaspididae	Sap-sucking insect	Fujian, Guangdong, Guangxi, Hong Kong, Taiwan, Macao
36	*Parlatoria oleae*		Diaspididae	Sap-sucking insect	Shaanxi, Xinjiang
37	*Quadraspidiotus perniciosus*		Diaspididae	Sap-sucking insect	Almost nationwide
38	*Matsucoccus* spp.		Margarodidae	Sap-sucking insect	East and Northeast China, and Yunnan
39	*Megastigmus sabinae*	Hymenoptera	Torymidae	Seed eater	Qinghai, Gansu
40	*Dryocosmus kuriphilus*		Cynipidae	Gall-making insect	Almost in all chestnut-producing areas
41	**Quadrastichus erythrinae*		Eulophidae	Gall-making insect	Taiwan, Guangdong, Hainan
42	**Leptocybe invasa*		Eulophidae	Gall-making insect	Guangdong, Guangxi, Hainan
43	*Aiolomorphus rhopaloides*		Eurytomidae	Gall-making insect	Zhejiang, Fujian, Jiangxi, Hunan
44	*Acantholyda posticalis*		Pamphiliidae	Defoliator	Mainly distributed in Heilongjiang, Henan, Shandong, Shanxi and Shaanxi
45	*Pristiphora erichsonii*		Tenthredinidae	Defoliator	Heilongjiang, Liaoning, Inner Mongolia, Shanxi
46	*Odontotermes formosanus*	Isoptera	Termitidae	Bark and root pest	Southern China
47	*Smerinthus planus*	Lepidoptera	Sphingidae	Defoliator	East and Northeast China, Inner Mongolia, Hebei, Henan, Jiangxi, Shaanxi, Ningxia and Gansu
48	**Hyphantria cunea*		Arctiidae	Woodborer	Liaoning, Shandong, Shaanxi, Shanghai, Tianjing, Hebei
49	*Carposina niponensis*		Carposinidae	Fruit eater	Mainly distributed in the fruit-producing areas in North and Northwest China
50	*Coleophora dahurica*		Coleophoridae	Defoliator	Northeast China, Inner Mongolia and Hebei
51	*Holcocerus hippophaecolus*		Cossidae	Woodborer	Liaoning, Inner Mongolia, Shanxi, Shaanxi, Ningxia, Gansu
52	*Apocheima cinerarius*		Geometridae	Defoliator	Xinjiang, Qinghai, Gansu, Shaanxi, Ningxia, Inner Mongolia, Hebei, Tianjing, Shandong
53	*Culcula panterinaria*		Geometridae	Defoliator	North, Northwest, Southwest and Central China
54	*Napocheima robiniae*		Geometridae	Defoliator	Shaanxi, Shanxi, Shandong, Henan and Hebei
55	*Atrijuglans hitauhei*		Heliodinidae	Fruit eater	Beijing, Hebei, Henan, Shanxi, Shaanxi, Sichuan, Guizhou

Table 1 continued

Number	Latin name	Order	Family	Feeding guilds	Distribution in China
56	**Opogona sacchari*		Hieroxestidae	Stem borer	Almost nationwide
57	*Cosmotriche saxosimilis*		Lasiocampidae	Defoliator	Yunnan
58	*Dendrolimus kikuchii*		Lasiocampidae	Defoliator	Southern China
59	*Dendrolimus latipennis*		Lasiocampidae	Defoliator	Yunnan, Guizhou, Sichuan, Zhejiang, Fujian, Hubei, Guangdong, Hunan
60	*Dendrolimus punctatus*		Lasiocampidae	Defoliator	Southern China
61	*Dendrolimus punctatus wenshanensis*		Lasiocampidae	Defoliator	Yunnan, Guizhou
62	*Dendrolimus spectabilis*		Lasiocampidae	Defoliator	Liaoning, Hebei, Shandong, Jiangsu, Taiwan
63	*Dendrolimus superans*		Lasiocampidae	Defoliator	Northeast China, Inner Mongolia, Hebei, Xinjiang
64	*Dendrolimus tabulaeformis*		Lasiocampidae	Defoliator	Beijing, Hebei, Liaoning, Shaanxi, Shandong, Shanxi, Sichuan
65	*Malacosoma neustria testacea*		Lasiocampidae	Defoliator	Northern China
66	*Lymantria dispar*		Lymantriidae	Defoliator	Mainly distributed in Northeast, North, Northwest and East China, and Taiwan
67	*Orgyia dubia*		Lymantriidae	Defoliator	Xinjiang
68	*Orgyia ericae*		Lymantriidae	Defoliator	Northeast China, Inner Mongolia, Shaanxi, Gansu, Ningxia, Qinghai, Shandong
69	*Parocneria furva*		Lymantriidae	Defoliator	Mainly distributed in Northeast, North, Northwest, East and Central China
70	*Parocneria orienta*		Lymantriidae	Defoliator	Zhejiang, Hubei, Sichuan
71	*Stilpnotia candida*		Lymantriidae	Defoliator	Almost nationwide with the exception of Guangdong, Guangxi and Hainan
72	*Leucoptera susinella*		Lyonetiidae	Defoliator	Northeast China, Hebei, Shandong, Henan and Inner Mongolia
73	*Cerura menciana*		Notodontidae	Defoliator	Mainly distributed in Northeast, North, East and Central China
74	*Clostera anachoreta*		Notodontidae	Defoliator	Almost nationwide
75	*Micromelalopha troglodyta*		Notodontidae	Defoliator	Northeast China, Hebei, Shandong, Henan, Jiangxi, Zhejiang, Jiangsu, Anhui and Sichuan
76	*Dichocrocis punctiferalis*		Pyralidae	Fruit eater	Almost nationwide
77	*Dioryctria pryeri*		Pyralidae	Feed cones and young shoots	Northeast, North and Northwest China, Anhui, Jiangsu, Zhejiang, Sichuan, Taiwan
78	*Dioryctria splendidella*		Pyralidae	Stem borer	Almost nationwide
79	*Paranthrene tabaniformis*		Sesiidae	Twig borer	Liaoning, Inner Mongolia, Shaanxi, Shanxi, Zhejiang, Jiangsu, Hebei, Beijing, Henan
80	*Sphecia siningensis*		Sesiidae	Woodborer	Qinghai, Gansu, Shaanxi, Shanxi, Inner Mongolia
81	*Synanthedon castanevora*		Sesiidae	Phloem-borer	Hebei, Beijing
82	**Cydia pomonella*		Tortricidae	Fruit eater	Gansu, Xinjiang
83	*Laspeyresia zebeana*		Tortricidae	Twig borer	North China, Heilongjiang, Jilin
84	*Zeiraphera griseana*		Tortricidae	Defoliator	North and Northwest China
85	*Zeiraphera lariciana*		Tortricidae	Defoliator	Hebei
86	*Ceracris kiangsu*	Orthoptera	Orthoptera	Defoliator	Southern China

Asterisks identify exotic invasive species

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